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CONTACT-DAMAGE COUPLED MODELLING OF FRP REINFORCEMENTS UNDER VARIABLE LOADING TIMES

G. MAZZUCCO[*], V.A. SALOMONI[*] AND C. MAJORANA[*]

[*] Department of Structural and Transportation Engineering
Faculty of Engineering, University of Padua
Via F.Marzolo, 9 – 35131 Padua.
e-mail: mazzucco@dic.unipd.it, salomoni@dic.unipd.it, majorana@dic.unipd.it

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Abstract. In the last years FRP (Fiber Reinforced Polymer) technology has been developed to repair damaged concrete structures. In this work it is proposed to investigate the complex mechanism of stress-strain evolution at the FRP interface, during different loading programs (short or long-time loadings), until complete debonding. This study has been performed by means of a fully three-dimensional approach within the context of damage mechanics, to appropriately catch transversal effects as well as normal stresses, developing a realistic and comprehensive study of the delamination process. The adhesion properties have been reconstructed through a contact model incorporating an elastic-damage constitutive law, relating inter-laminar stresses acting in the sliding direction. A F.E. research code (FRPCON) has been developed, including a numerical procedure accounting for Mazars's damage law inside the contact algorithm. The code is able to describe the delamination process considering the different surface preparation of the concrete part as well. The long-time behaviour of these composite structures has been studied by means of two visco-elastic formulations: i) Bazant's B3 law has been considered for the concrete component, where creep effect is composed by three different terms, i.e. the elastic part, basic creep and drying creep; ii) for FRP's fibres and matrix a micromechanical approach has been implemented. The experimental results of long-time bending tests have been used to calibrate and validate the numerical models.

1 INTRODUCTION

The externally bonded fibre reinforced polymer (FRP) technology has been successfully used in the last years, particularly for recovering structures. In civil engineering practice, this method (generally used for masonry and concrete materials) can be subjected to delamination phenomena: the rupture is localized in the first concrete's layer close to the FRP, named interface zone. In literature several studies of stress field evolution at the interface, obtained in close forms [1, 2] and *via* numerical models [3-6], can be found. Generally, the delamination process in flexural beams is influenced by shear stress concentration at the joint, normally evaluated experimentally by single or double shear tests [7, 8] or bending tests [8].

The contribution of surface preparation in concrete beams (before FRP bonding) to increase strength, as proposed in [9-11], is a new aspect which can be considered for a deeper understanding of the delamination mechanism. Different techniques of surface preparation aim to increase concrete's roughness at the interface zone, allowing for a better bonding with FRP and an increasing strength under ultimate limit loads.

A three-dimensional finite element code has been specifically developed to simulate debonding processes, influenced by surface preparation, by means of a contact-damage algorithm [3, 11] able to represent the entire delamination progression under short or long time applied loads. Transient analyses to simulate long term effects have been carried out considering visco-elastic materials characterized by different compliance functions, for concrete materials (by using B3's theory [12]) and for FRP materials (by using a micromechanical theory developed in [13]) as well. For additional information on long term analyses see [11].

2 THE DELAMINATION PROCESS

Delamination is a progressive detachment of FRP sheets from concrete surface after exceeding the joint strength. Experimental evidences [9, 10] establish that delamination normally affects a thin layer of concrete close to FRP sheets (i.e. at the interface), due to the fact that the maximum shear stress of concrete is smaller than the adhesive's one. From the numerical point of view, the interface can be represented with a physical constant thickness (t_a) known as *adhesive layer* or, as previously stated, *interface zone* [5-8]. In standard practice, concrete surface is subjected to mechanical treatments for enhancing the asperities before FRP bonding, hence increasing adhesion strength (Figure 1 a). After bonding, the real adhesive thickness depending on concrete surface's roughness does not result constant along the joint, hence it appears as more appropriate to assume t_a as the average asperity height (Figure 1 b), so including concrete and adhesive as well.

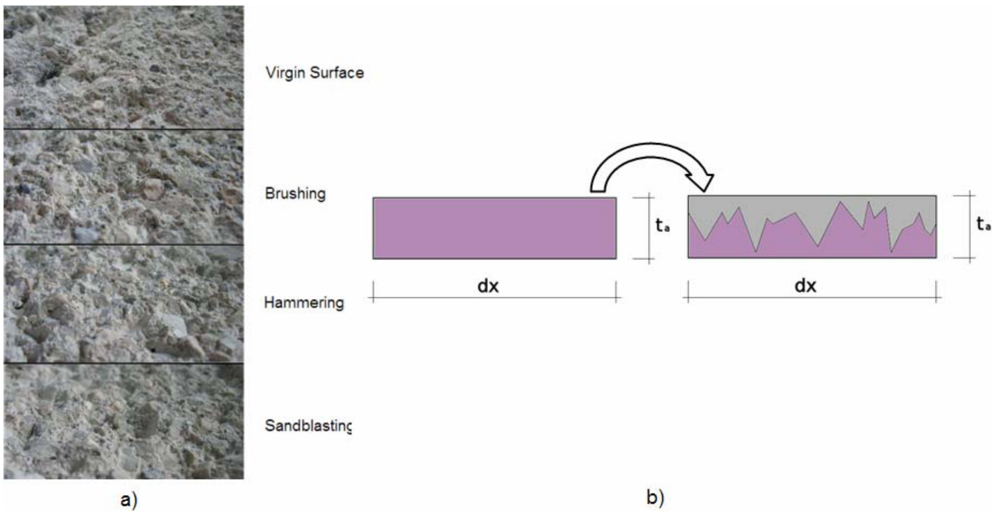


Figure 1: a) Different types of surface treatment; b) interface thickness with asperity inclusions.

If the interface zone is considered as composed by adhesive and concrete (i.e. asperities), necessarily homogenised, the constitutive characteristics can be assumed as

$$\mathbf{D}^C = \mathbf{D}^C(V_c, V_a)$$
$$D_{ij}^C = \frac{D_{c,ij} V_c^{\%} + D_{a,ij} V_a^{\%}}{V_c^{\%} + V_a^{\%}} \quad (1)$$

where V_c is the volume of asperities, V_a the volume of adhesive, $V_k^{\%}$ the volumetric percentage of k-material (k = a, c) and $D_{k,ij}$ are the constitutive tensor components of k-material.

3 CONTACT MODEL

FRP-concrete bonding at the interface has been numerically modelled by means of the contact mechanics theory. If considering two bodies, Ω^1 and Ω^2 (Figure 2), e.g. representative of concrete and FRP, two surfaces can be identified, Γ^1 (with $\Gamma^1 \in \Omega^1$, named *slave*) and Γ^2 (with $\Gamma^2 \in \Omega^2$ named *master*), where contact is possible. The *closed contact* condition is achieved and the two bodies are in contact if the contact surface $\Gamma^C = \Gamma^1 \cap \Gamma^2 \neq 0$.

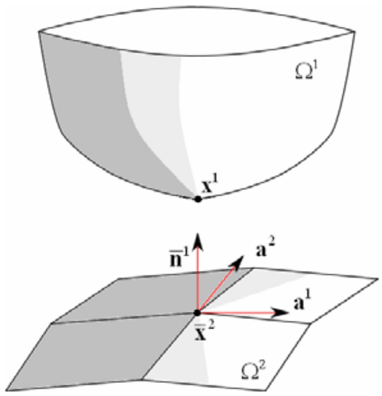


Figure 2: Contact condition.

Contact is defined considering the fundamental conditions [14]:

- Non-penetration conditions

$$\begin{aligned} &\left(\bar{\mathbf{u}}^2 - \mathbf{u}^1\right)\cdot \mathbf{n}^1 + g \geq 0 \quad on \ \Gamma_c \\ &g = \left(\bar{\mathbf{X}}^2 - \mathbf{X}^1\right)\cdot \mathbf{n}^1 \quad on \ \Gamma_c \end{aligned} \tag{2}$$

where $\mathbf{u}^i$ (with i = 1, 2) are the displacement vectors, $\mathbf{X}^i$ the vectors' position in the reference configuration, g the gap function (the distance between two points in contact) and $\mathbf{n}$ the normal vector (Figure 2).

- Action-reaction conditions

$$\mathbf{t}^2 + \bar{\mathbf{t}}^1 = 0 \quad on \ \Gamma_c \tag{3}$$

where $\mathbf{t}^i$ are the stress vectors.

- Kuhn-Tucker conditions

$$\left[\mathbf{t} - \left(\mathbf{D}^C : \boldsymbol{\varepsilon}\right)\mathbf{n}^1\right]\left[\left(\bar{\mathbf{x}}^2 - \mathbf{x}^1\right)\cdot \mathbf{n}^1\right] = 0 \quad on \ \Gamma_c \tag{4}$$

where $\mathbf{D}^C$ is the constitutive tensor and $\boldsymbol{\varepsilon}$ the strain tensor of the interface (which has a physical volume, as explained in the previous Section).

In the developed three-dimensional numerical code, characterized by quadratic brick elements (20 nodes), master and slave surfaces have been defined by the faces of brick elements (Figure 3). The closed contact condition have been considered in the *contact pair*, defined through a slave node and a master point where the gap function g is evaluated.

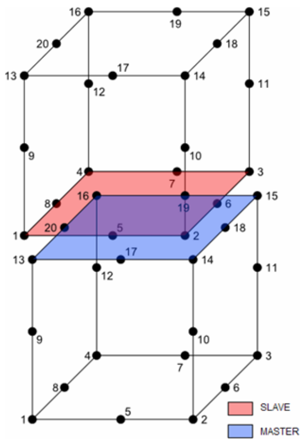
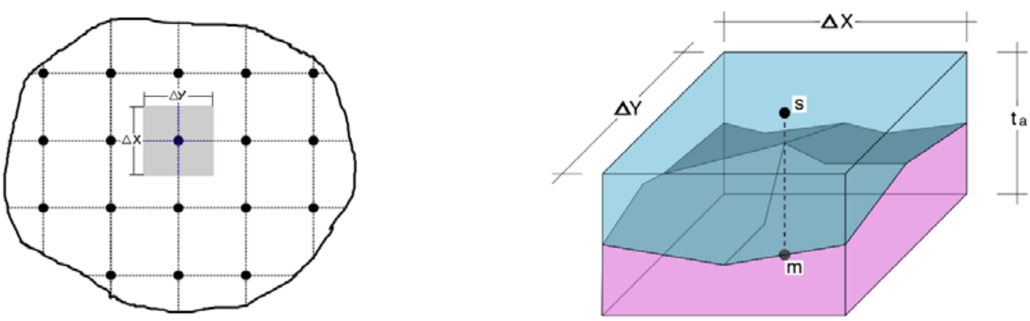


Figure 3: Master and slave surfaces in brick elements.

The master point $\bar{\mathbf{x}}^2$ in a contact pair is chosen as the point with a minimum distance from the slave node $\mathbf{x}^1$; generally it does not coincide with a master *node* but with a generic point belonging to Γ^2. If the gap function value is less than a minimum distance, the contact is defined as closed. To describe concrete-FRP adhesion by means of a contact algorithm, the minimum distance for considering closed contact has been assumed equal to the asperity height t_a.

To associate stress and strain tensors to the interface zone at each slave node (and for every contact pair) an *element* with volume $\Delta V = \Delta x \cdot \Delta y \cdot t_a$ has been considered, where the base $S = \Delta x \cdot \Delta y$ is geometrically defined by mesh discretization (Figure 4 a) and the volume's height has been assumed equal to t_a (Figure 4 b).



a) b)

Figure 4: a) Reference base at the interface in the discretized slave surface; b) typical *interface volume* for every contact pair (concrete plus adhesive).

The strain tensor has been evaluated by considering linear displacement variations inside

ΔV [2]; the stress field at the interface between FRP and concrete has been defined once slave and master displacement components for every contact pair (u^s, v^s, w^s, u^m, v^m, w^m), as well as the constitutive tensor $\mathbf{D}^C$, had been known

$$\boldsymbol{\sigma} = \mathbf{D}^C : \boldsymbol{\varepsilon} \tag{5}$$

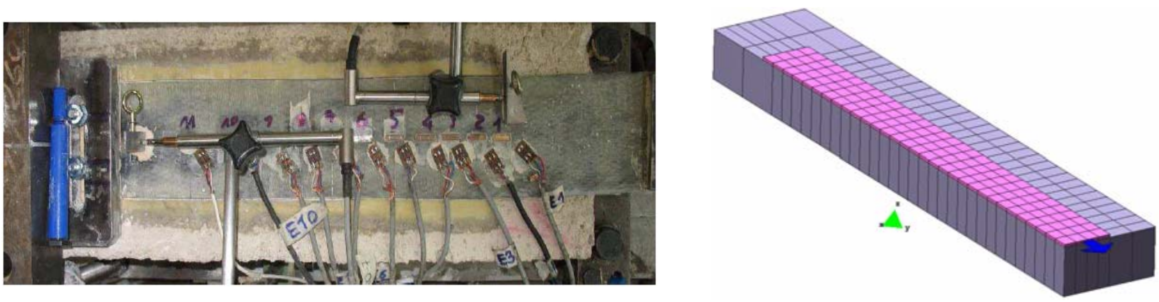
4 DAMAGE MODEL

A contact procedure alone is not sufficient to simulate the stress-strain evolution at the contact zone during delamination processes. Considering that the detachment between FRP and concrete occurs in the first concrete layer closed to the joint, to represent the loss of adhesion the Mazars' damage law [15] (not reported here for sake of brevity) has been associated to the contact algorithm. In this way bonding/debonding phenomena are driven by the evolution of damage at the interface.

Being the mechanical characteristics of the interface zone during delamination dependant on damage variable d, the tensor $\mathbf{D}^C$ is correspondingly modified by damage, $\mathbf{D}^C = \mathbf{D}^C(d)$. Hence delamination occurs if, during loading, the damage variable assumes a unit value at a *contact pair*: the contact is consequently open.

5 MODELS AND RESULTS

Numerical models have been carried out to first calibrate and then validate the procedure with available experimental results [9]. The setup of the single shear test (Figure 5) consisted in one concrete prism 100×100×300 mm^3 connected to one 50 mm wide sheet of carbon fiber-reinforced polymer (CFRP).



a) b)

Figure 5: a) Experimental single shear test; b) adopted discretization.

Several types of surface preparation have been considered with different asperity heights (see Table 1).

Under an increasing applied load, the elastic state is overcome at the interface and subsequently delamination starts; the damage evolution of Figure 6a is representative of the delamination process, characterized by a typical shear stress distribution (Figure 6 b).

A comparison between experimental and numerical results in terms of ultimate loads has hence confirmed the correctness of the adopted procedure (Table 1).

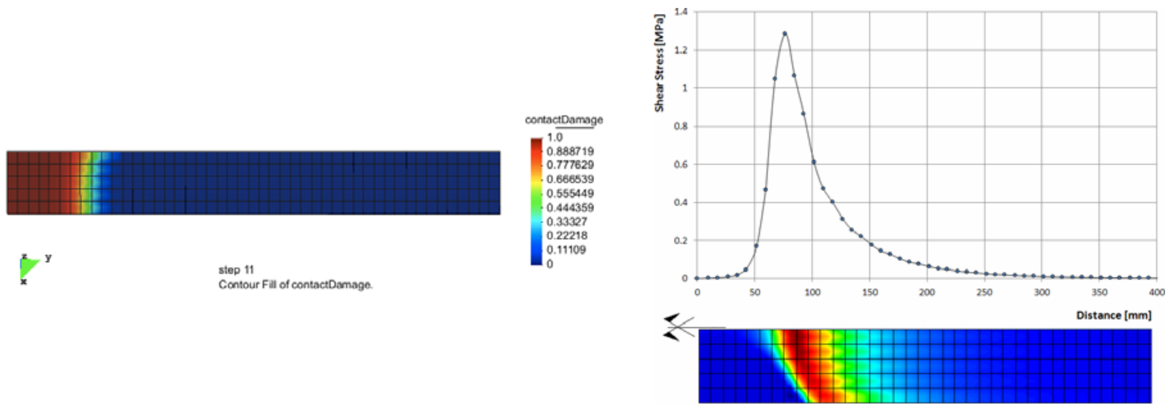
Experimental bending tests on concrete beams reinforced by FRP sheets under long time loads [11] have been additionally considered for validating the model. The bending test setup is reported in Figure 7, where 100×100×600 mm^3 concrete prisms have been strengthened by

50×400 mm^2 carbon fibres sheets (their thickness has been evaluated in 0.165 mm).

The numerical simulations have accounted for a viscous behaviour for the considered materials; specifically, model B3 [12] has been chosen for representing concrete creep and a micromechanical model [13] for FRP sheets creep as well.

Table 1: Experimental and numerical ultimate limit loads with different surface preparation techniques.

Surface preparation technique	*Asperity height t_a [mm]*	*Experimental Ultimate load [kN]*	*Numerical Ultimate load [kN]*
Sandblasting	2.7	25.31	25.89
Hammering	2.4	23.48	22.98
Brushing	1.6	17.62	15.85



a) b)

Figure 6: a) Damage evolution during debonding; b) interface shear stresses.

Numerical strains at the joint have been compared with experimental strains evaluated at strain gauges, externally applied to the CFRP reinforcement; Figure 8 refers to strain gauge 1 (applied at 5 mm from the middle of the beam).

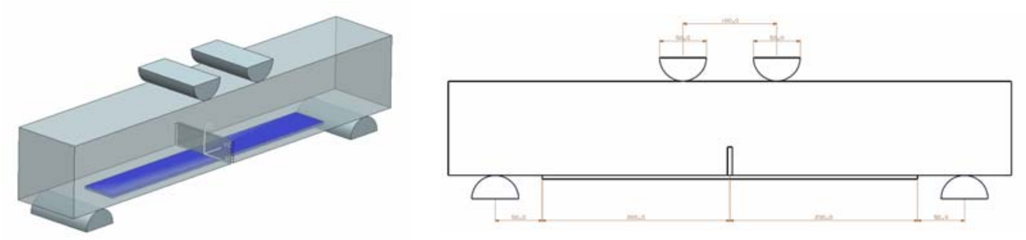


Figure 7: Bending test setup.

6 CONCLUSIONS

Composite beams, made of concrete strengthened with FRP sheets, have been here investigated considering short and long time applied loads, starting from already available experimental evidences and referring to a specifically developed 3D numerical model. The whole system (concrete plus FRP and adhesive) has been represented via three different physical objects: the concrete base, the interface zone composed by adhesive and concrete asperities and the strengthening bonded FRP strip. The adhesion between layers has been modelled by means of a contact model whose elastic-damage constitutive law relates interlaminar stresses acting in the sliding direction. Long term effects have been studied considering appropriate compliance functions (B3 model for concrete and a micromechanical model for FRP). The research F.E. code has demonstrated to be able to simulate delamination processes and long time stress-strain evolutions. By comparing the numerical results with those of a wide experimental investigation, in terms both of ultimate load and strain vs. time, it has been shown that such an approach is able to catch delamination from a three-dimensional point of view and its evolution during the entire loading process.

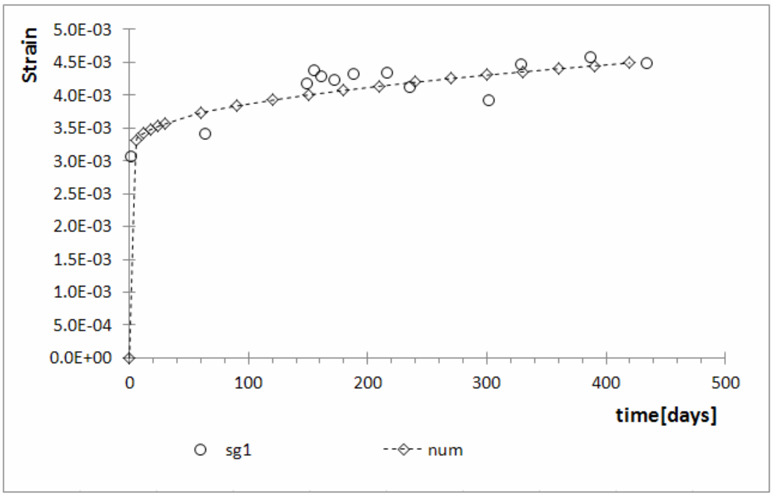


Figure 8: Comparision between experimental and numerical interfacial strains.

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